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RESEARCH MEMORANDUM

SOME CONSIDERATIONS REGARDING THE APPLICATION OF THE SUPERSONIC AREA RULE TO THE DESIGN OF AIRPLANE FUSELAGES

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

This paper presents certain considerations and techniques pertinent to the application of the supersonic area rule to the design of airplane fuselages. Among the more important factors considered are an extension of the rule to account for the interference effects of the wing and tail on the general flow field for asymmetrical configurations, the determination of fuselage area developments which result in approximately the minimum wave drag, and the influence of wing parameters and design Mach number on the effectiveness of fuselage shaping. Experimental results obtained with various fuselage shapes are presented to indicate the effectiveness of the application of the supersonic area rule when utilizing these considerations.

INTRODUCTION

As an extension of the transonic area rule (ref. 1), a supersonic area rule has been developed (refs. 2 and 3). This rule states that the wave drag of a wing-body-tail combination at a given supersonic speed is related to longitudinal developments of cross-sectional areas as intercepted by Mach planes. Published (refs. 4 and 5) and unpublished wind-tunnel and flight results obtained for a number of configurations indicate that fuselage shaping based on the proper application of this rule result in significant reduction in wave drag throughout the flight speed ranges of the various configurations.

Since the publication of the basic rule, a number of additional considerations and techniques regarding its application to the design of airplane fuselages have been developed. These considerations do not invalidate the basic idea of the supersonic area rule as previously published but allow a more effective application of this relation to the design of fuselage contours of practical aircraft. No rigorous theoretical justifications are presently availa[redacted]considerations, which, for

the most part, are based on physical reasoning. However, limited experiments indicate that usually these considerations provide improved drag characteristics. In the present report, an attempt has been made to summarize these various considerations and techniques.

DETERMINATION OF AREA DEVELOPMENTS

Supersonic Area Rule

On the basis of the supersonic area rule, the zero-lift wave drag for an airplane is related to the longitudinal developments of the normal components of cross-sectional area as intercepted by Mach planes inclined at the angle m as shown in figure 1. The various developments are obtained with the axis of tilt of these planes rolled to various positions around the center line of the configurations (θ in fig. 1). For clarity, the position of the axis of tilt of the Mach plane is maintained and the configuration is rolled. This procedure is illustrated in figure 1. According to the supersonic area rule, the wave drag for the combination is the average value of the drags of the area developments so determined. Of course, this result is only approximate. The supersonic area rule is not exact even within the approximations of linear theory. However, for many configurations, it accounts for the major part of the wave drag and has provided a useful tool in the search for low-drag airplanes.

The principal effect not accounted for by the supersonic area rule is that of reflected waves. Thus, in the supersonic-area-rule approximation, it is assumed that disturbances emanating from the wing or fuselage are not influenced by the presence of the wing, fuselage, or tail. In reality, some of the disturbances are reflected by these components. The supersonic area rule would be improved if procedures for accounting for these neglected effects could be incorporated into the rule. In the next section, a simple method is presented for estimating the effect of reflections produced by the wing and tail. Generally, the reflections produced by the body are extremely complex, and no simple method has been developed for handling these effects. However, the influence of these reflections is usually small compared with those produced by the wing and tail.

The application of the supersonic area rule may be simplified without a significant loss in effectiveness beyond that associated with disregarding the reflected effects of the body by considering only the cross-sectional areas of the fuselage intercepted by normal cuts. The application of the rule is further simplified without significant loss in effectiveness by using for wing cross-sectional areas the areas of sections normal to the plane of the wing through the intersection of the Mach planes with the plane of the wing. (See fig. 2.)

Effect of Reflections Produced by the Wing or Tail Surfaces

The problem of reflections of disturbances by the wing or horizontal tail for asymmetrical configurations is illustrated by the sketch in figure 3. Shown is the side view of a symmetric wing in combination with a fuselage indented only above the wing. Most of the disturbances from the indentation above the wing which are directed downward are reflected upward by the wing as shown; thus, the body shaping above the wing should have little effect on the flow below the wing and an exaggerated effect above the wing. (For symmetrical configurations, the reflection of disturbances produced by changes in the fuselage shape below the wing replaces the disturbances produced by the upper part which could not pass through the wing. For such configurations, the reflection effects are accounted for by the basic area rule.)

The adverse effects that may be associated with such reflections of disturbances by the wing for asymmetrical configurations are illustrated by the zero-lift drag results presented in figure 4, which were obtained from reference 6. A delta wing having symmetrical airfoil section was investigated in combination with an unindented fuselage and two indented fuselages. In one case the normal cross-sectional areas of the wing were removed axially symmetrically from the fuselage. In the other case the total wing cross-sectional areas were removed only above the wing. With the asymmetrical indentation, the incremental drag coefficient ΔC_{D_O}, which is based on fuselage frontal area, was considerably higher than that for the symmetrical indentation throughout the Mach number range of the test. Further, the asymmetric indentation produced adverse effects on the drag compared with those obtained with no indentation at Mach numbers above 1.1. Similar adverse effects would be expected for an airplane configuration with symmetrical wing sections with fuselage shaping concentrated above or below the wing. For lifting conditions, an asymmetric fuselage of the type shown in figure 4 may result in reductions in wave drag.

For the usual design conditions, the problem of determining these reflected effects exactly is extremely complex since the reflection is only partial. However, a reasonable approximation of the effect is obtained by assuming that the reflection is complete for disturbances originating in the region of the wing and is not present for disturbances produced by the fuselage ahead of and behind the wing root. With such an assumption, the areas of the fuselage above and below the plane of the wing are considered separately; while ahead of and behind the wing, the complete fuselage areas are utilized. Such a procedure is strictly applicable only when the wing leading edge is supersonic. However, experimental results for several asymmetrical configurations, including those presented in figure 4, have indicated that fuselage contours based on these separate area developments provide increased reductions in drag even at lower Mach numbers. The areas above and below the horizontal tail are separated in a similar manner.

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It seems reasonable that the plane through the leading and trailing edges of the wing root section should probably be used as the plane of division of cross-sectional areas. Also, reasonably, the areas should be divided above and below the wing at fuselage stations between those at which Mach planes intersecting the leading and trailing edges of the juncture sections of the surface cross the center line (E and F in fig. 5).

The cross-sectional areas to account for the reflected disturbances above or below the wing or tail plane can be estimated by the method of images. Consider a cross section through a wing-fuselage combination as shown in figure 6. Within the simplifying assumption described earlier, the flow in the region above the wing plane is the same as that for a wing fuselage composed of the area development above the wing plane plus its mirrored image. Then the effects of the reflected waves are estimated by considering a configuration having twice the areas of the wing and fuselage above the wing plane. A corresponding procedure is utilized to obtain the areas for below the wing plane.

In general, the combining of the area developments above or below the wing or tail planes with the complete areas for the fuselage ahead or behind the wing or tail to form complete area developments will result in discontinuous developments (shown by the dashed line in fig. 7). These discontinuities do not represent real effects of the asymmetric configuration on the flow. Since the wave drag is related to the longitudinal rate of change of cross-sectional area rather than to the cross-sectional area, the real effect is approximated by shifting the areas, as shown in figure 7, so that area developments are continuous.

The cross-sectional areas for cambered wings are also divided, with the areas of the wing above the chord plane considered separately from those for below this plane. The wing areas above or below the chord plane are considered with the corresponding fuselage areas. The favorable effects on drag that may be obtained through the use of fuselage contours designed on the basis of such divided areas for a cambered wing are illustrated in figure 8. The cambered 45° sweptback wing of reference 5 was tested in combination with two contoured bodies. The wing has an aspect ratio of 4.0, a taper ratio of 0.15, an NACA 64A206, $a = 0$ section at the root, and an NACA 64A203, $a = 0.8$ (modified) section from the 50-percent semispan to the tip. The wing is placed symmetrically on the bodies. The total cross-sectional areas for the two bodies were essentially the same. One body was shaped symmetrically to obtain favorable total area distributions by using complete wing cross-sectional areas; the other body was shaped asymmetrically to obtain favorable area developments above and below the wing plane by utilizing divided wing cross-sectional areas. Since the area for the cambered wing above the chord plane is greater than that below, the indentation of the fuselage above

the wing is deeper than that below. The design Mach number was 1.4. The results for a Mach number M of 1.43 presented in figure 8 indicate that the asymmetrical indentation results in improvements in the drag coefficients C_D throughout the range of lift coefficient C_L. The reductions in drag at lift coefficients are larger than those obtained near zero lift. Such modifications also generally provide changes in the characteristics of lift coefficient and pitching-moment coefficient C_m in the positive direction, as shown in figure 8, which should have a favorable effect on the trim drag for most configurations at supersonic speeds.

Usually, for asymmetric configurations, fuselage modifications intended to reduce the wing or tail disturbances are concentrated near the wing or tail rather than being distributed around the fuselage periphery. In order to define the most satisfactory longitudinal development of modifications thus concentrated, the cross-sectional areas for the wing or horizontal tail usually should be combined with the fuselage areas at the longitudinal stations where the oblique cutting planes for the wing or tail (for example, A in fig. 9) cross the plane of lateral symmetry and the plane of the wing or tail (B in fig. 9). Also, fuselage modifications intended to reduce the disturbances of the vertical tail are usually concentrated near the base of that surface. For such cases, the cross-sectional areas of the vertical tail usually should be combined with fuselage areas at the stations where the tail cutting planes cross the upper surface of the fuselage in the region of the tail. During the investigation of a high-wing airplane configuration, it was found that a fuselage modification designed on the basis of the area distributions obtained by combining areas in this manner resulted in significantly lower drag than did a modification obtained by combining the areas where the oblique cutting planes crossed the center line of fuselage.

Number of Cutting Planes

Analysis of fuselage contour designs made with varying numbers of area developments has indicated that usually the changes in the fuselage lines obtained by using more than three area developments for the upper or lower parts of the configuration should not result in significant reductions of the drag beyond those obtained with three. The most effective application of the area rule would probably be realized by utilizing equally weighted developments obtained with cuts for values of θ (see fig. 1) of 15°, 45°, and 75°. Such cuts define the approximate mean developments for 30° segments of a quadrant. However, sufficiently accurate approximations of the results obtained using such cuts are arrived at by utilizing the cuts for $\theta = 0^{\circ}$, 45°, and 90°. These latter cuts are usually more readily obtained. In arriving at an average drag coefficient or area distribution, twice as much weight is given the distribution corresponding to the 45° plane since this distribution defines the average conditions in spa[redacted]r the other distributions.

Internal Flow

Several experimental investigations (refs. 7 and 8) have demonstrated that the equivalent stream tube area for the air swallowed by the engine air inlet should be subtracted from the total area development for the configuration from the air inlet to the exit (fig. 10) to obtain the most satisfactory interpretation of the wave drag using area development.

For most airplanes the general stream flow usually separates from the fuselage surface at the corner of the jet exit. Beyond this station jet and separated flow displace the unseparated stream. The general displacement of the stream generally expands downstream. For configurations with nacelle-mounted engines, displacement of the jet may have a significant influence on the drag. For such cases, such an expansion of the jet should be taken into account. However, for the calculation of the wave drag for configurations with bases which form the end of the effective area development, the addition of constant area at the base would seem satisfactory for the present. This area is obtained by subtracting the stream-tube area entering the inlet from the base area (fig. 10).

SELECTION OF DESIRABLE LONGITUDINAL AREA DEVELOPMENT FOR FUSELAGE

Basic Approach

In order to obtain the optimum fuselage cross-sectional area development for a symmetric airplane near the speed of sound, the single wing and tail areas are subtracted from the total or envelope area development which is indicated to have minimum drag characteristics for the fixed conditions for the configuration. However, at a given supersonic speed, the wing or tail has a number of area developments which may differ considerably. Consequently, a given fuselage area development cannot provide ideal total developments for each of the wing developments. A compromise fuselage area development must be utilized. Lomax and Heaslet have determined analytically (ref. 9) that, for the ideal conditions of fixed total volume and length, the optimum compromise development is obtained by subtracting the average of the area developments for the wing and tail from the total or envelope area development calculated to have minimum wave drag for such conditions. Experimental results for several configurations have indicated a similar conclusion (refs. 5 and 10, for example). It may be assumed that for the fixed conditions of practical airplanes, the optimum fuselage area development is obtained in a similar manner.

Envelope Area Development

For most practical airplane configurations, the cross-sectional areas are usually fixed near the nose, in the midregion, and near the tail as shown in figure 11. Obviously, in the midregion, the fixed area includes the average wing areas superimposed on fixed fuselage areas, whereas near the rearward end of the airplane, the average tail areas are added to the fuselage area. At supersonic Mach numbers for the fineness ratios utilized for practical aircraft, the slender-body theory does not provide a reliable indication of the area development for minimum wave drag for such fixed conditions; therefore, the nonslender linear theory should be utilized. However, because of the extreme complexity of this more inclusive theory, its use for the computation of the exact minimum-drag developments for these fixed conditions is impractical at present.

Recently, Parker (ref. 11) has used this more exact nonslender theory to compute the minimum-drag developments for the similar but simpler conditions of fixed lengths and fixed maximum area. Approximations of the developments for the fixed conditions of practical airplanes may be obtained through a consideration of the developments for these simpler conditions. Although such developments depend on fineness ratio and Mach number, for the values of fineness ratio of practical interest and for Mach numbers from 1.2 to 2 (the probable range in which fuselage contours will be designed on the basis of the area rule) the shapes are approximately the same. The shape for a mean condition of these ranges is shown in figure 12. This shape is based on an interpolation of shapes obtained by Parker. It may be noted that this development has a corner and consists of approximately straight lines over most of the length. This suggests that the minimum-wave-drag envelope for the fixed conditions shown in figure 11(a) might be approximated by fairing straight lines tangent to the fixed area developments as shown.

For many configurations, the maximum slopes of the average area development of the wing may not be sufficiently great to allow straight line tangents to be drawn to this development. Such a condition is shown in figure 11(b). It seems reasonable that for such cases an arc, tangent to the development near the peak, as shown, would provide a satisfactory envelope area development. Also, when the wing area distribution extends along the rearward end of the airplane, this wing area must be added to the fixed fuselage and tail areas to define the proper envelope. (See fig. 11(b).)

The effects of fuselage modifications based on several envelope area developments (fig. 13) have been determined during the tests of an airplane with 42° swept wings (fig. 14). One envelope utilizes the straight-line fairings based on nonslender-body theory as just discussed; the other approximates that which would have minimum wave drag based on slender-body theory. The design Mach number was 1.2. The incremental minimum wave-drag coefficients, which are [redacted] area, for Mach numbers to 1.2 are presented in figure 13. [redacted]s indicate that the fuselage

[redacted]

contours based on the straight-line-fairing envelope produce significantly lower wave drag than did the contours based on the approximation of the slender-body theory. Before the nonslender-body theory became available, the use of the straight-line envelope rather than the slender-body-theory minimum-drag envelope was proposed as a means for improving the drag at off-design conditions. Experimental results for several configurations (fig. 13 and unpublished results) indicate that the use of such an envelope in preference to one based on slender-body theory reduces the wave drag at off-design conditions considerably more than at the design conditions.

Fuselage Area Developments

The determination of the fuselage area developments for asymmetric configurations is considerably simplified by first arriving at an axial development of total fuselage areas assuming no reflections by the wing or tail. The procedure described in the preceding section is utilized. Then, in the region of the wing and tail the total area for the fuselage is divided above and below the wing or tail so that the changes in average area for these separate regions are the same as for the design envelope. For symmetric wings or tails, this requires that the changes of area for the fuselage in these separate regions be made equal. For asymmetric or cambered wings, the fuselage shape is further modified by subtracting the average changes of areas for the asymmetry from one side of the wing and adding to the other.

With the use of an envelope as described, the indentation of the fuselage area development in the region of the wing is usually relatively shallow compared with the maximum average cross-sectional area of the wing. For the example illustrated in figure 13, the indentation amounts to only 10 percent of the maximum average wing cross-sectional area. In some cases, a fuselage area distribution with no indentation but with a relatively flat portion in the region of the wing may result in satisfactory wave drags over a range of supersonic speeds. Such a shape would be required for the conditions shown in figure 11(b). The reductions in drag associated with the use of these fuselage contours with little or no indentation may be attributed to the pressure fields produced by the special longitudinal variations in the slopes of these area developments. Usually, changes in the slopes of the fuselage area developments are relatively gradual along the forebody, the midportion and in the region of the tail, but relatively severe near the leading edges of the root sections of the wing and tail surfaces (fig. 13). For some cases, the changes may be relatively severe near the trailing edge of the wing-root section.

CROSS-SECTIONAL SHAPING OF FUSELAGE

For the applications of the simple supersonic area rule to the design of aircraft fuselages, certain methods have been used for the cross-sectional shaping of the longitudinal changes in fuselage area developments intended to offset the wing and horizontal-tail disturbances. When feasible, such changes have been concentrated on the sides of fuselage. When the depth of the fuselage side above or below the wing or tail is relatively small, such a procedure may result in excessive changes of the slopes of the lines of the fuselage sides, undesired increases in the fuselage wetted area, and unwieldy distributions of fuselage volume. For such conditions, the required changes in the fuselage area development have been distributed around the top or bottom of the fuselage as well as on the sides. As an example, for the high-wing airplane configuration shown in figure 14 the fuselage side below the wing was sufficiently deep to allow all the required changes in area to be concentrated on the sides; however, above the wing, all the required changes in area were, of necessity, placed on the top of the fuselage.

Where possible, the changes in the fuselage area development intended to offset disturbances produced by canopies, stores, nacelles, fairings, and other similar components producing changes in the area developments should be placed as close as possible to these components.

Recently, several more comprehensive theories have been developed by Lomax and Heaslet (ref. 9) and Nielsen (ref. 12) which provide means for determining special nonaxially symmetric distributions of volume of the fuselage which result in lower wave-drag coefficients for fuselage-wing-tail combinations than those obtained with fuselage shaping based on the supersonic area rule. The overall actual wave-drag characteristics of practical airplanes at the various operating speeds and altitudes may be further improved by the use of feasible fuselage shaping based on these more comprehensive theories.

INFLUENCE OF AIRPLANE DESIGN PARAMETERS

ON EFFECTIVENESS OF FUSELAGE SHAPING

Effect of Wing Design

The range and relative magnitude of the favorable effects of body shaping based on the supersonic area rule are markedly influenced by the wing configuration, as pointed out in reference 2. Comparisons of a number of experimental results (ref. 4, for example) have indicated that the general overall effectiveness of body shaping is usually greater with increased wing or tail le[redacted]. Also, comparisons of

unpublished experimental results have shown that the relative effectiveness of body shaping is larger with the centroids of the cross-sectional areas of the wing or tail closer to the fuselage. Such inward positions of these centroids are generally associated with lower aspect ratios and taper ratios of the plan forms and the use of spanwise reduction in the section thickness ratios from root to tip. Greater wing sweep or inward positions of the centroids generally causes the area distributions for the wing and tail surfaces for the various values of θ at the various Mach numbers to approach more nearly the average distribution used to design the fuselage contours. Thus, the irregularities in the area distributions for these various conditions are less, as described in reference 2, and the wave drag is less.

It is known that increased plan-form taper and some spanwise variation in the section thickness ratio have favorable effects on the weight of a wing with a given aspect ratio and mean thickness ratio. Because of these effects, most airplanes incorporate wings with considerable taper in plan form and generally some taper in thickness ratio. As a result of the additional favorable effect of such tapers on the effectiveness of body shaping, it is probable that for configurations with contoured bodies, these tapers should be greater than those considered optimum on the basis of analysis of the structure and aerodynamics of the wing only.

Selection of Design Mach Number

The design Mach number for the fuselage contour which would provide the optimum compromise performance for the range of operation of an airplane is dependent on the relative importance of operations at the various conditions and the effectiveness of the shaping at these conditions. Unfortunately, little information is available on the effectiveness of various body shapes for wide ranges of conditions. Until such information is obtained, it would seem advisable to design the contour for a specific Mach number equal to a weighted average operational speed, within the limitations discussed below.

Comparisons of area developments and limited experimental results (ref. 10, for example) have indicated that, when a fuselage is shaped on the basis of the supersonic area rule for a Mach number significantly greater than that for which the leading edge becomes supersonic, the reduction in drag at the design condition is generally only slightly greater than that obtained at this speed with a shaping designed for a Mach number less than the critical value. On the other hand, the reductions in drag at Mach numbers below this critical value obtained with such a shaping are considerably less than those resulting from shapings designed for these lower speeds, particularly at Mach numbers near 1.0.

Therefore, the fuselage should generally not be designed for a Mach number significantly greater than this critical value, even though the average operating speed of the airplane may be well beyond this speed.

EXPERIMENTAL RESULTS

In order to illustrate the general effectiveness of shaping the fuselage on the basis of the supersonic area rule when utilizing the considerations described in the preceding sections, the incremental drag-rise coefficients of the airplane configuration shown in figure 14 with unmodified, partially modified, and finally modified fuselage contours based on these considerations are presented in figure 15. The results were obtained in the 8-foot transonic pressure tunnel at transonic Mach numbers up to 1.2 and at a Mach number of 1.43. The design Mach number was 1.2. The results presented are for lift coefficients near the minimum drag conditions. As indicated by the area developments, the partial modification included revisions to the forward and rearward portions of the fuselage, the final modification included additional modification to the midportion of the fuselage. The average of the drag-rise increments for this example configuration for Mach numbers from 1.00 to 1.43 was reduced by 0.0027 or 10 percent by the partial modification and by 0.0068 or 25 percent by the final modification. The basic drag at subsonic speeds was essentially unaffected. Drag reductions of the same order as those shown were generally obtained at lift coefficients up to 0.4.

CONCLUDING REMARKS

Several of the more important indications of the foregoing analysis are as follows: In order to obtain the greatest reductions in drag by utilizing the area rule, the area developments for the wing and fuselage above and below the wing- or tail-chord planes should be considered separately; in order to obtain the fuselage area development which provides the approximate minimum wave drag for a usual airplane configuration at moderate supersonic speeds, the average wing and tail areas are subtracted from an envelope or total area development constructed by fairing approximately straight lines to the usual regions of fixed areas; and, in order to obtain the lowest drag for a range of Mach numbers, the maximum design Mach number for the fuselage contours should generally be less than that at which the leading edge of the wing becomes supersonic.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., May 10, 1956.

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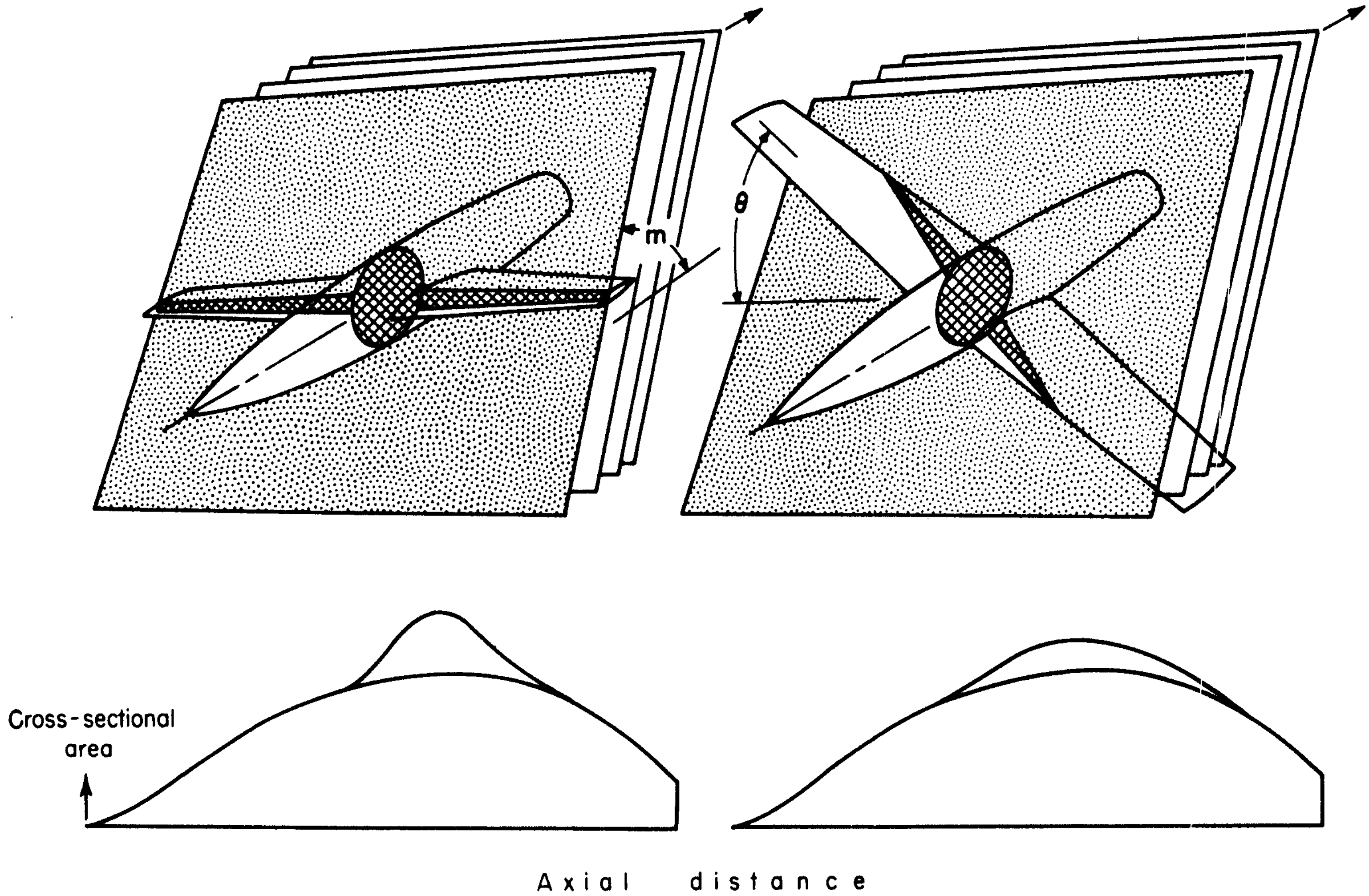


Figure 1.- Illustration of procedure for determining area developments related to wave drag at supersonic Mach numbers.

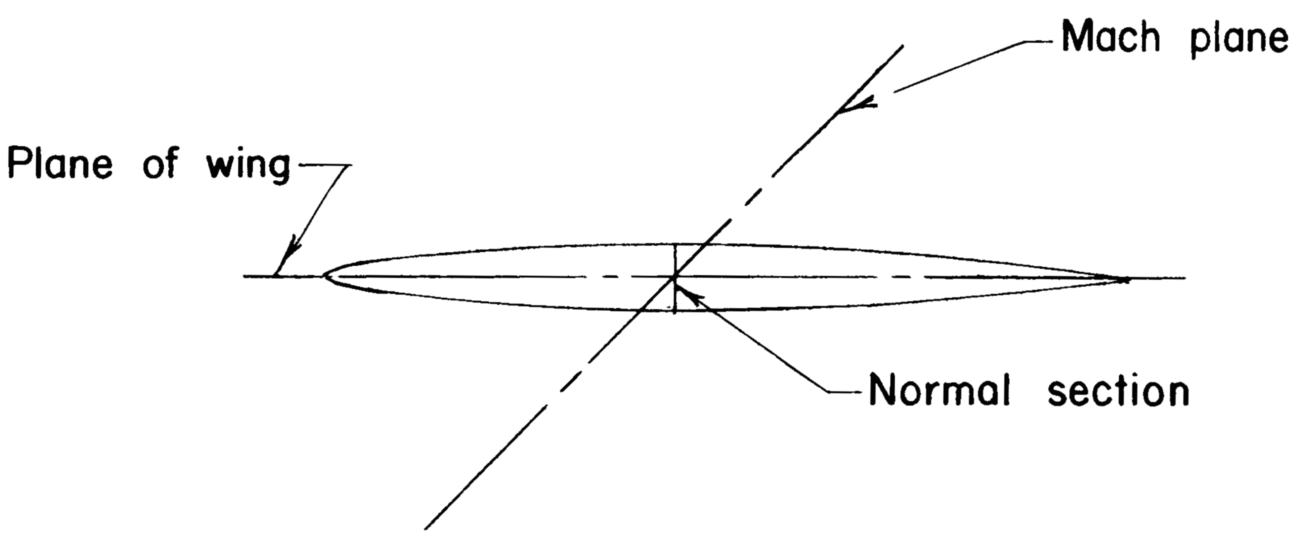


Figure 2.- Sketch illustrating simplification of procedure for obtaining wing-section areas.

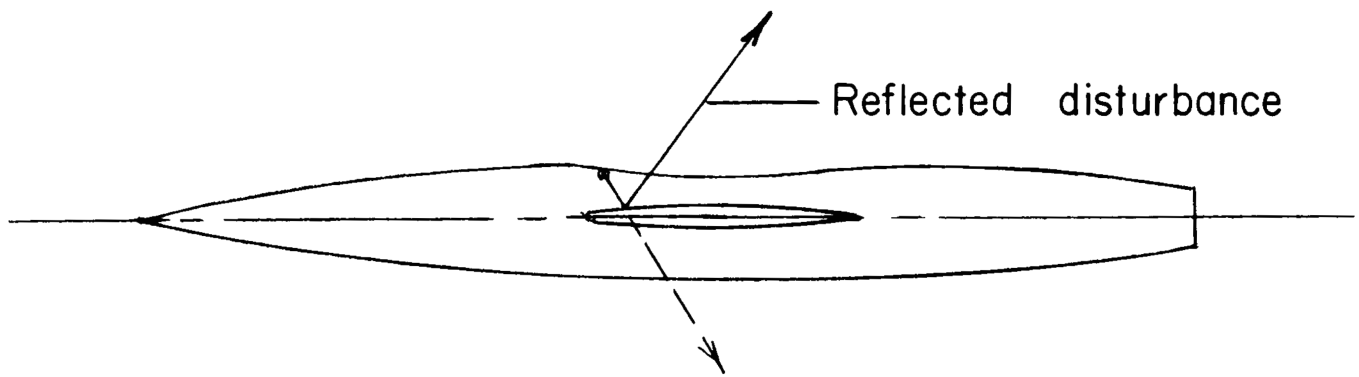


Figure 3.- Sketch illustrating reflection of disturbances by wing for asymmetric configuration.

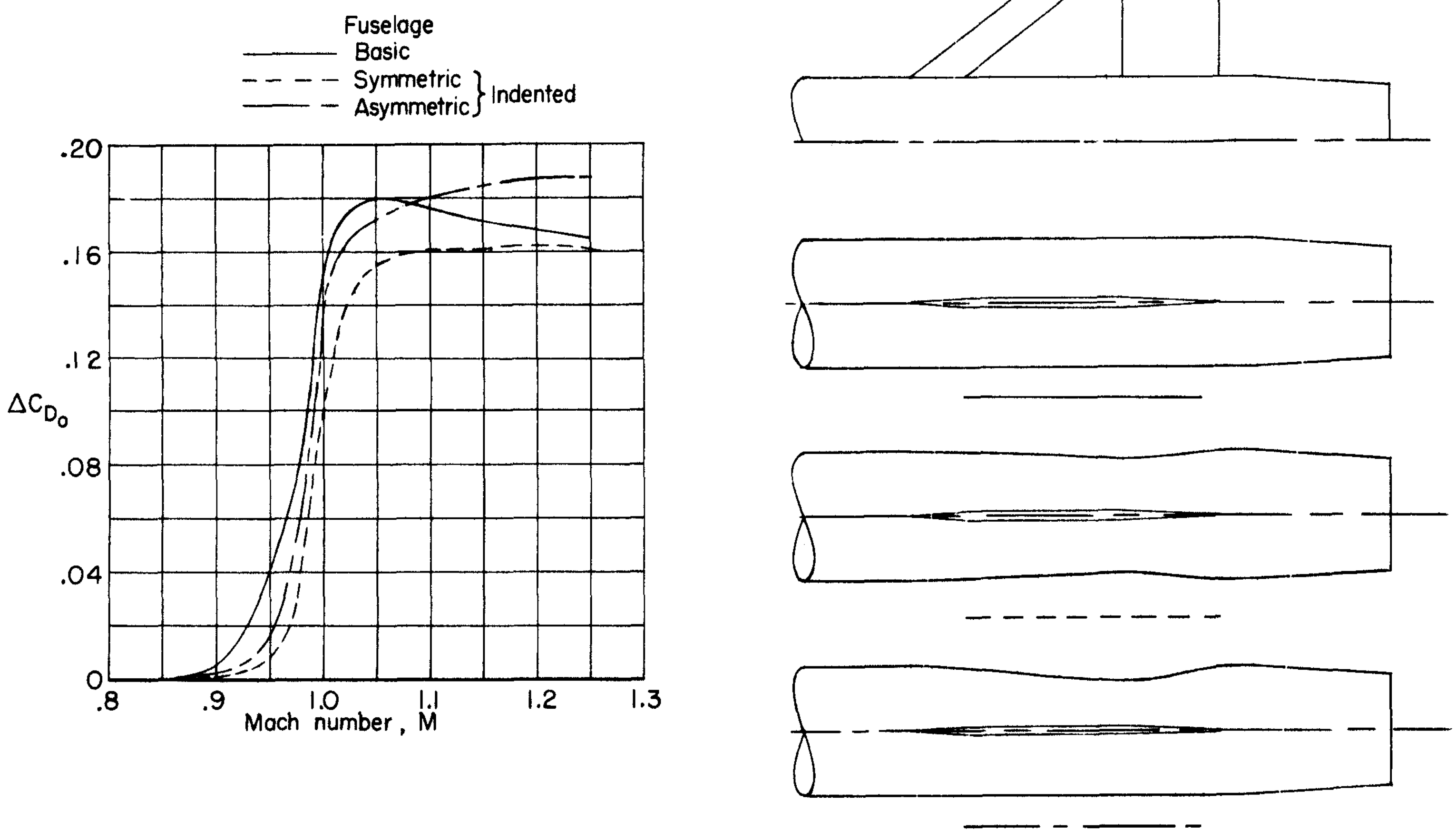


Figure 4.- Effect on wave drag of asymmetric fuselage indentation with wing having symmetrical airfoil sections.

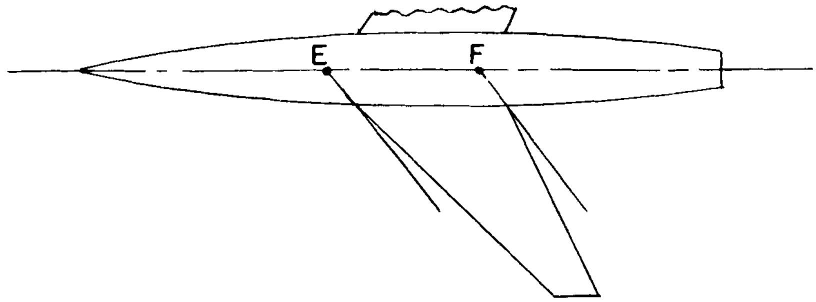


Figure 5.- Sketch indicating the region of division of areas above and below wing plane.

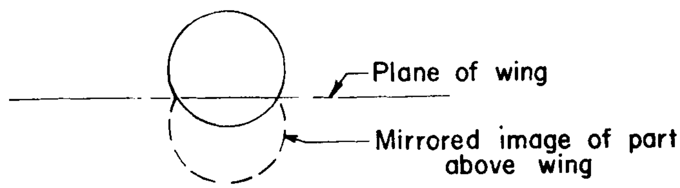


Figure 6.- Sketch indicating procedures used to account for reflected effects.

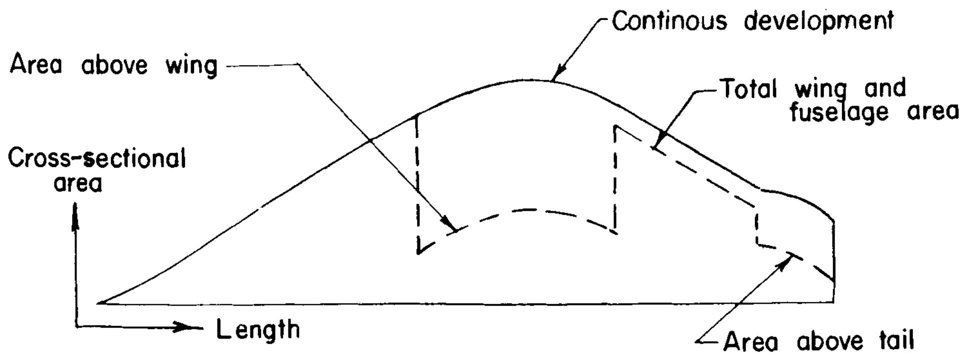


Figure 7.- Sketch illustrating procedure for obtaining continuous area developments above or below wing or tail planes.

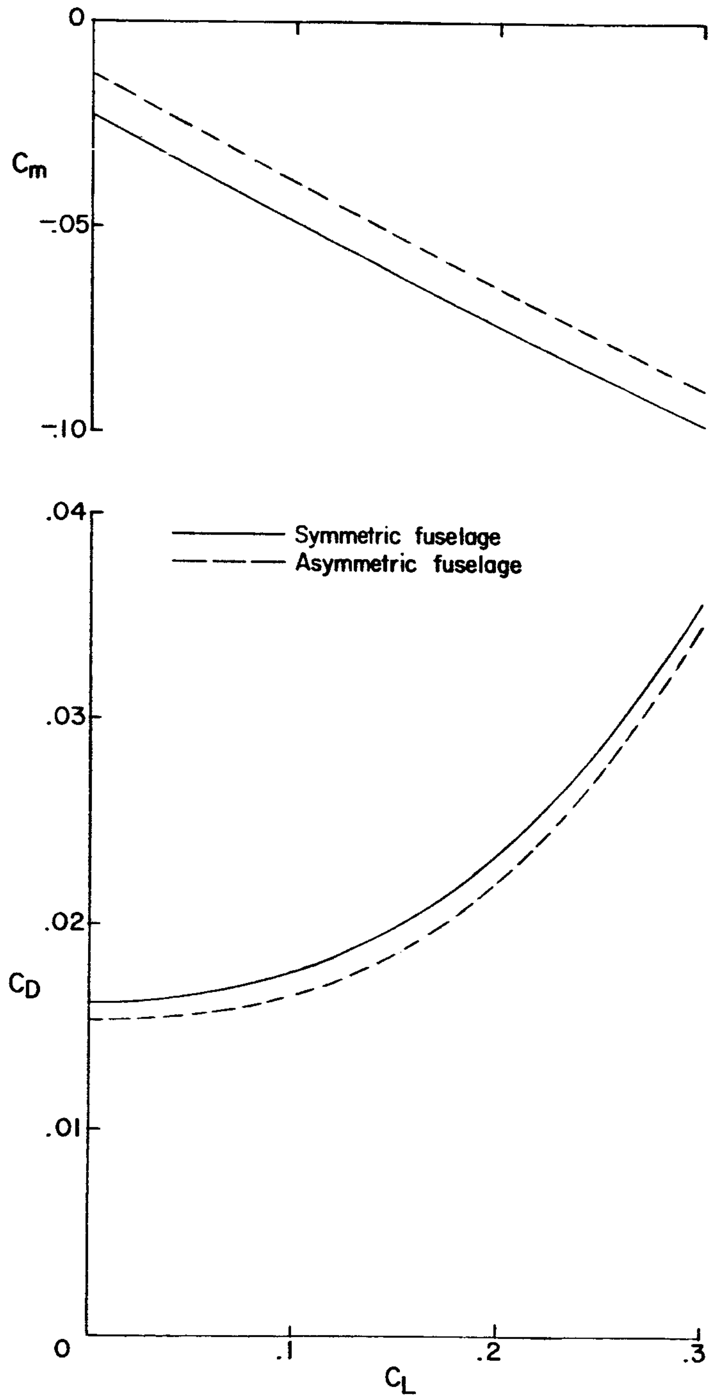


Figure 8.- Comparison of drag and pitch results obtained for symmetric and asymmetric fuselage modifications with cambered swept wing. M = 1.43.

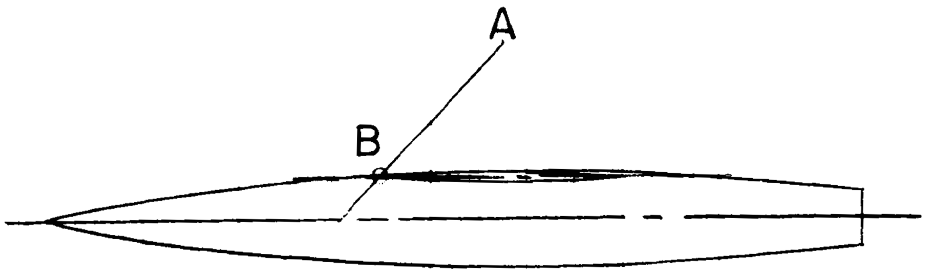


Figure 9.- Illustration of method of locating cross-sectional areas of wing longitudinally.

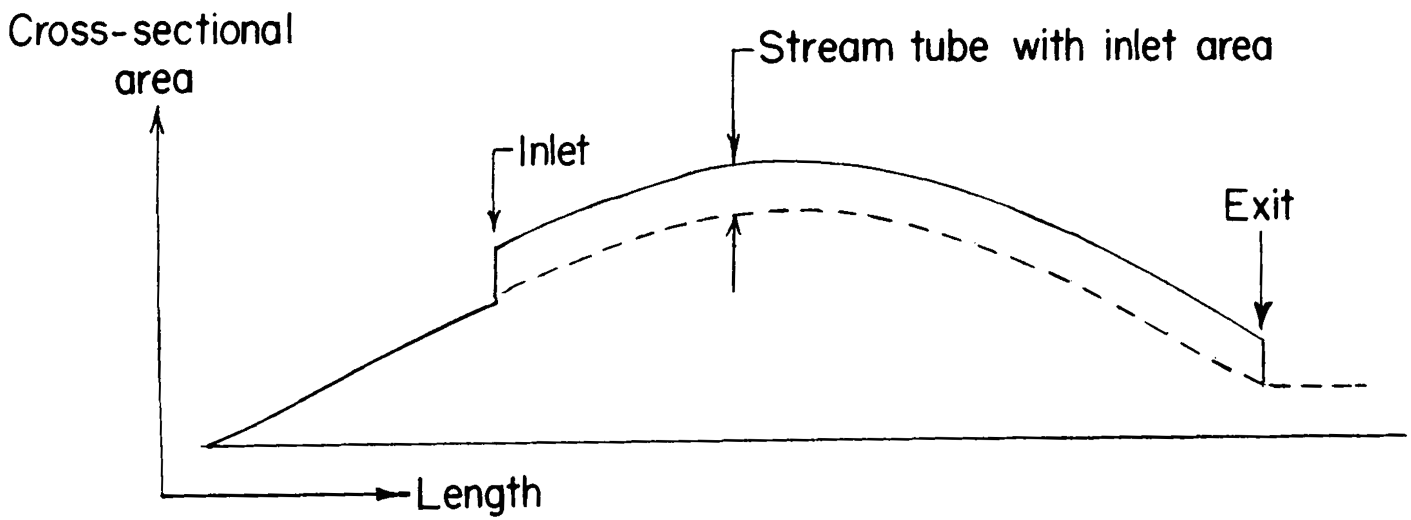
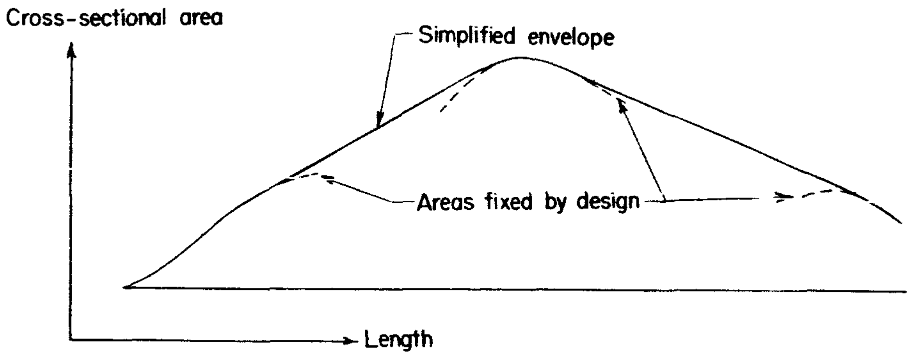
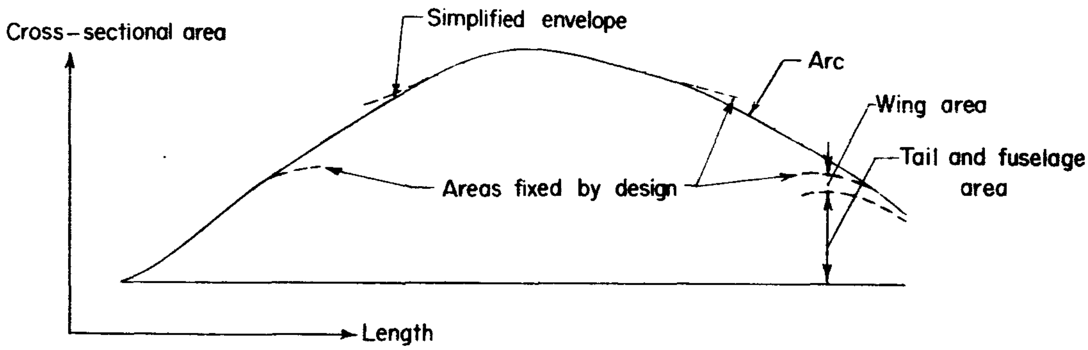


Figure 10.- Illustration of procedure for accounting for internal flow.



(a) Basic method.



(b)Modified method.

Figure 11.- Illustration of procedure for determining the simplified minimum-wave-drag envelope for fixed conditions of practical configurations.

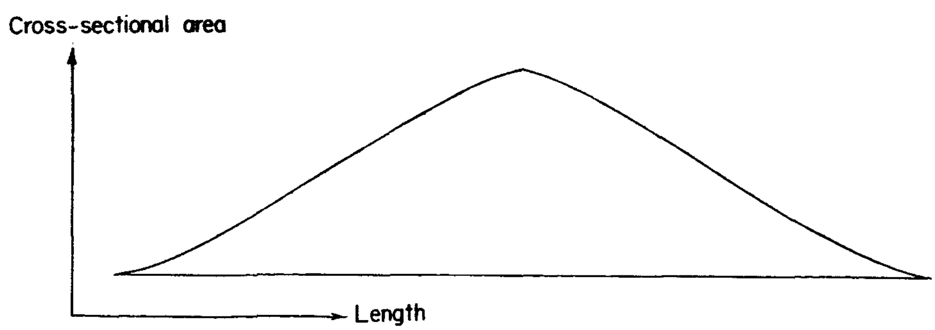


Figure 12.- Area development for minimum wave drag based on interpolation of nonslender linear theory; length and maximum area at 0.5 length fixed. $M = 1.4$; length to maximum diameter = 10.

[redacted]

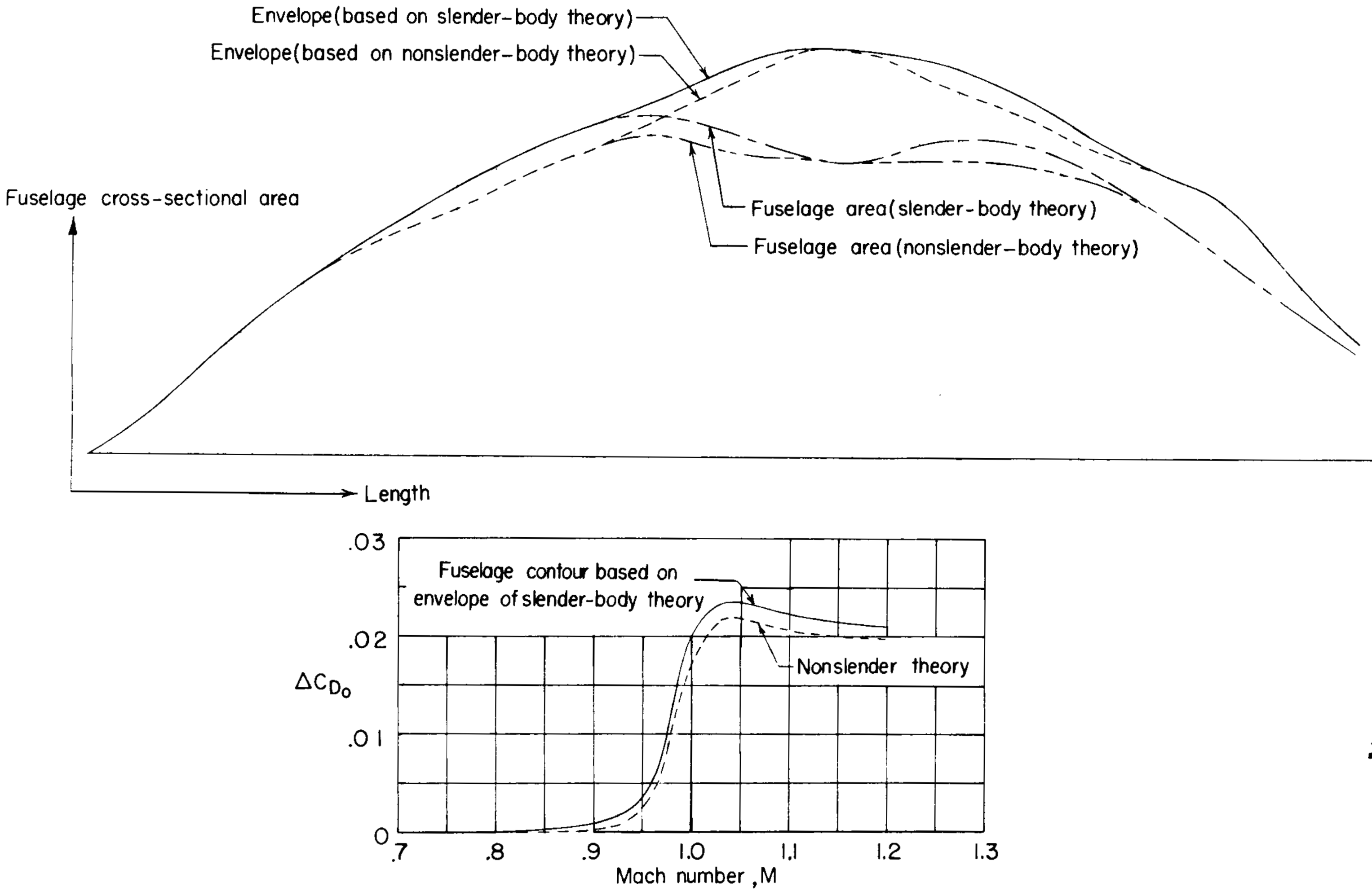


Figure 13.- Effect of envelope shape on wave drag for a swept-wing airplane configuration.

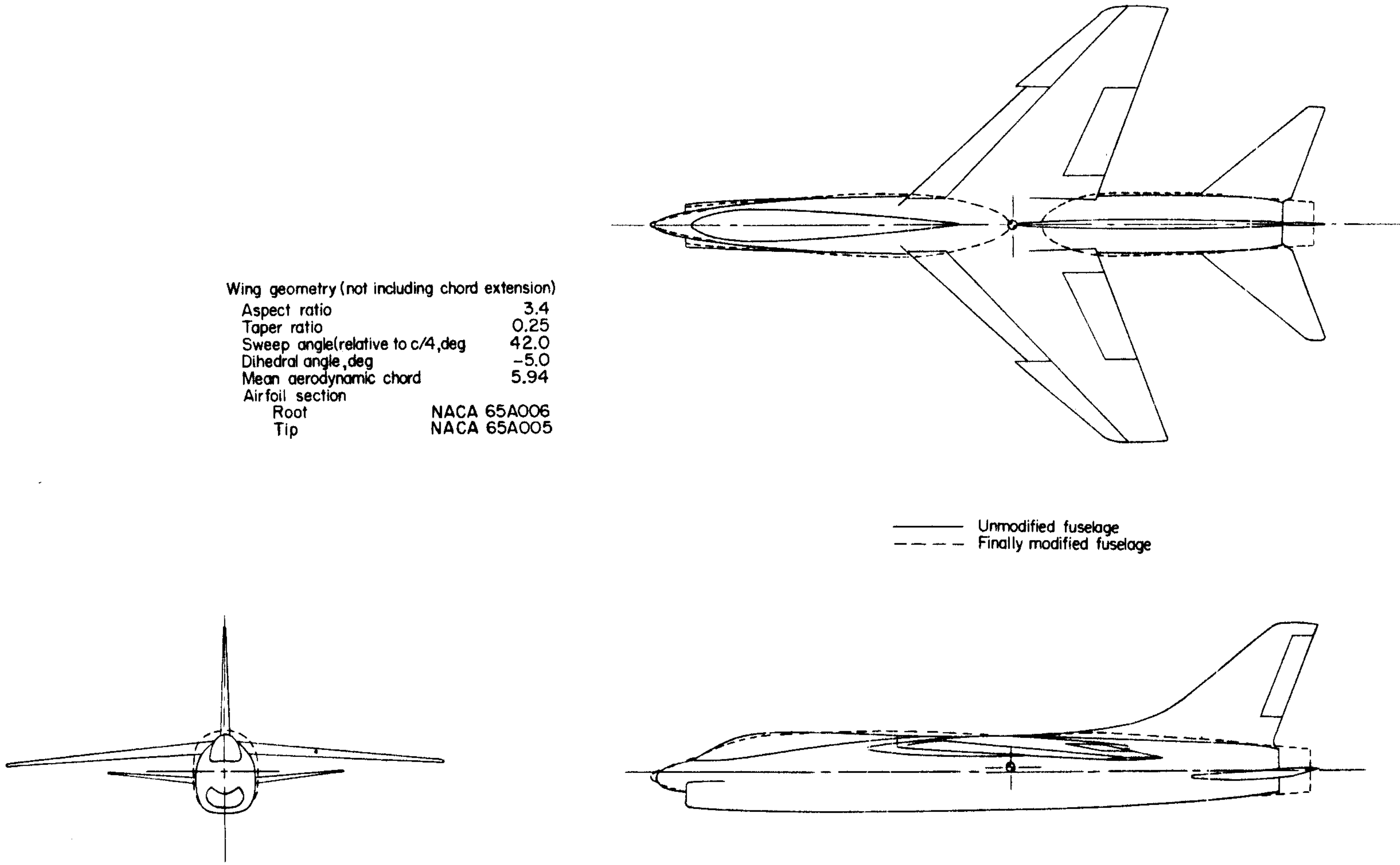


Figure 14.- Three-view sketch of the swept-wing fighter-type airplane configuration used as an example with the unmodified and finally modified fuselage contours.

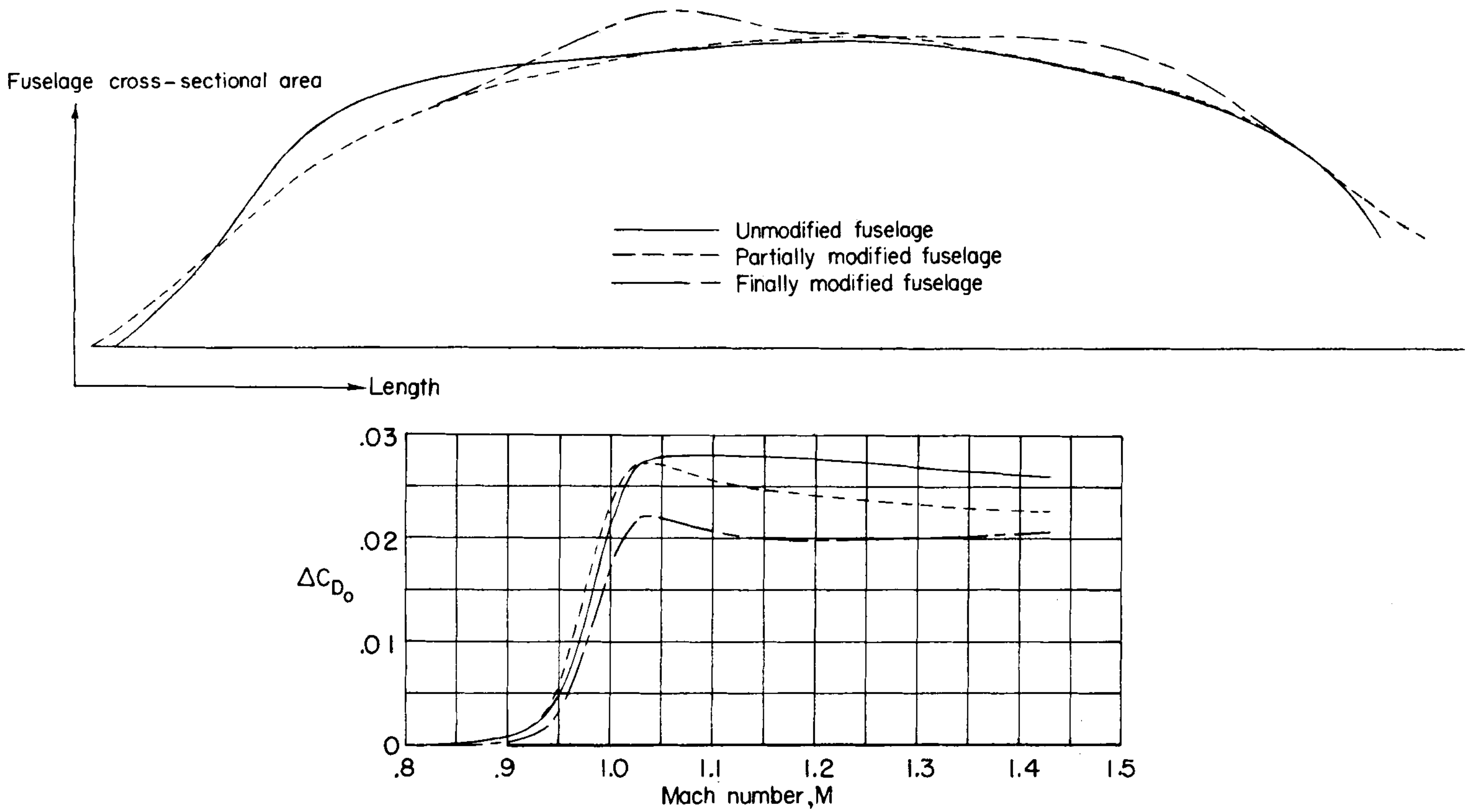


Figure 15.- Fuselage area development and incremental drag-rise characteristics for example airplane configuration with unmodified, partially modified, and finally modified fuselage contours.

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